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ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60440

A SUMMARY REPORT ON NEUTRON RADIOGRAPHY

by

Harold Berger

Metallurgy Division

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A SUMMARY REPORT ON NEUTRON RADIOGRAPHY

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I. INTRODUCTION

A development program concerned with techniques for neutron radiography has been in progress at this Laboratory since 1960.[1] This report summarizes this program thus far and indicates the wide variety of applications of this inspection method.

Interest in neutron-radiographic inspection methods was originally stimulated by the knowledge that the relative absorption of neutrons and X radiation in materials is quite different.[2-5] Such difference was particularly well demonstrated by Thewlis' plot of mass absorption coefficients for the elements for both neutrons and X rays,[4,5] shown in Figure 1.

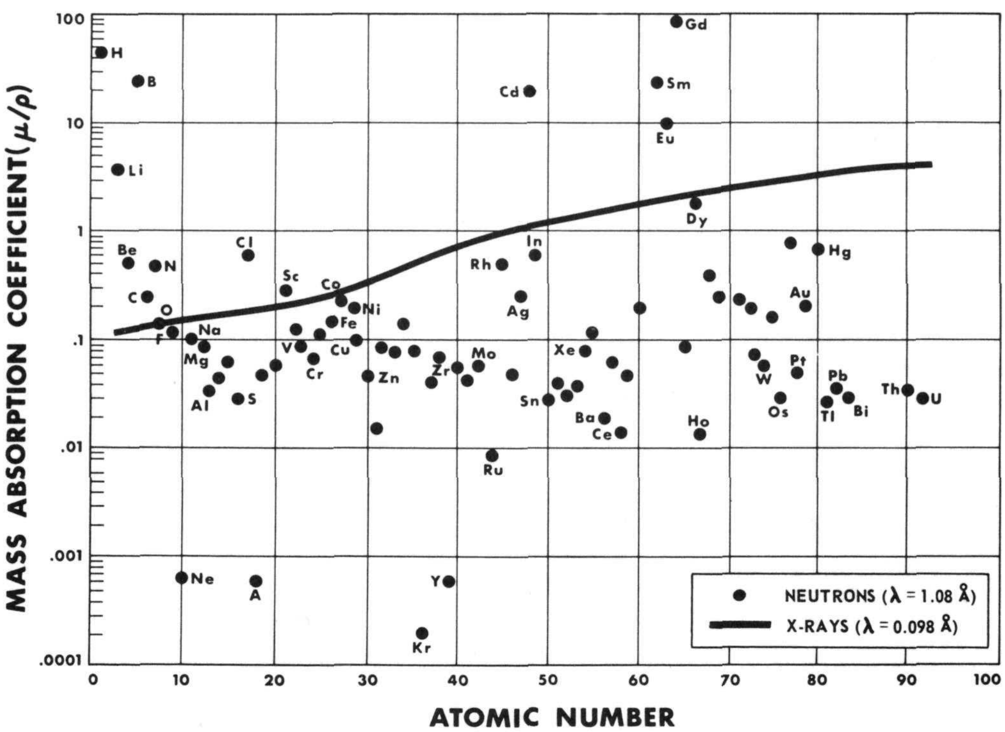

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Figure 1. The Mass Absorption Coefficients of the Elements are Plotted against Atomic Number for Both X Rays (Solid Line) and Thermal Neutrons (Circles)

The obvious differences suggest a number of possible applications. Those suggested by Thewlis[4,5] include the inspection of large thicknesses of heavy metals with decreased exposure time as compared with conventional radiographic methods (because of the low absorption of neutrons in these materials), the detection of hydrogen, lithium, or boron in heavier materials, and the possibility of better radiographic discrimination between neighboring materials in the periodic table, such as boron and carbon, or cadmium and barium. The first material in each of these groups has much greater absorption for neutrons than the other material, whereas the X-ray-absorption characteristic for each material in a mentioned pair is very similar.

Studies in each of these mentioned areas indicate that the anticipated advantages of thermal neutron radiography for such inspections can be realized. A number of specific application studies are discussed later in this report. In addition, the reader is referred to an extensive list of possible application areas for neutron radiography given by Watts.[6]

The absorption differences illustrated in Figure 1 involve neutrons of approximately thermal energy. For neutrons of higher energy many of these large differences in material absorption characteristics are appreciably diminished, so that the use of fast neutrons is less attractive for general radiographic applications. Although it is true that resonance-energy neutrons could be used to provide even greater attenuation differences for specific materials, as was pointed out by Watts,[6] there are difficulties involved in producing reasonably monochromatic neutron beams* of sufficient intensity for radiography in this energy region. This discussion, therefore, will be concerned primarily with the use of thermal-neutron radiography.

A further limitation is that the detection methods discussed are primarily photographic. Although other methods are possible,** the present state of the art is such that photographic techniques appear to yield the most satisfactory results.[7]

II. METHODS OF PHOTOGRAPHIC DETECTION

Methods of photographic detection for thermal-neutron images have included the use of loaded (usually with boron or lithium) emulsions and normal X-ray films, both alone and in conjunction with various converter materials. The converter-material technique is preferred because the neutron response of presently available normal or loaded emulsions used

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*Such beams should be monochromatic if they are to provide the excellent discrimination possible in the resonance-energy region.

**Reviews of such methods have been given by Berger[1] and Watts.[6]

alone is relatively poor from a speed point of view. The converter materials perform the function of changing the neutron image into some radiation more readily detectable by the film. Such techniques can improve the neutron response of an X-ray film by several orders of magnitude. A comparison of many of these detection methods has been given previously.(7,8)

The converter materials normally used for neutron detection and some of their characteristics are listed in Table I. These materials are essentially of two different types, prompt emission and potentially radioactive. The prompt-emission materials, such as the gamma emitters cadmium and gadolinium and the alpha emitters lithium and boron, must be exposed to the neutron beam with photographic film. The film must be present during the actual neutron exposure in order to detect the radiation promptly emitted from these screen materials. This technique has been termed the direct exposure method and is useful not only with the materials specifically mentioned, but with all the converter materials listed in Table I. The technique is illustrated in Figure 2.

Table I[a]

CHARACTERISTICS OF SEVERAL NEUTRON PHOTOGRAPHIC IMAGE INTENSIFIER MATERIALS

Material	Isotope Involved in Reaction	Relative Natural Abundance (%)	Cross Section for Reaction (thermal neutrons, velocity = 2,200 m/sec)	Reaction[b]	Half-life
Lithium	Lithium-6	7.52	910	$^{6}Li(n,\alpha)^{3}H$	
Boron	Boron-10	18.8	3,770	$^{10}B(n,\alpha)^{7}Li$	
Rhodium	Rhodium-103	100	12	$^{103}Rh(n)^{104m}Rh$	4.5 min
			140	$^{103}Rh(n)^{104}Rh$	44 sec
Silver	Silver-107	51.35	44	$^{107}Ag(n)^{108}Ag$	2.3 min
	Silver-109	48.65	2.8	$^{109}Ag(n)^{110m}Ag$	270 d
			110	$^{109}Ag(n)^{110}Ag$	24.2 sec
Cadmium	Cadmium-113	12.26	20,000	$^{113}Cd(n,\gamma)^{114}Cd$	
Indium	Indium-115	95.77	155	$^{115}In(n)^{116m}In$	54.1 min
			52	$^{115}In(n)^{116}In$	13 sec
Samarium	Samarium-149	13.8	40,800	$^{149}Sm(n,\gamma)^{150}Sm$	
	Samarium-152	26.8	140	$^{152}Sm(n)^{153}Sm$	47 hr
Gadolinium	Gadolinium-155	14.73	61,000	$^{155}Gd(n,\gamma)^{156}Gd$	
	Gadolinium-157	15.68	240,000	$^{157}Gd(n,\gamma)^{158}Gd$	
Dysprosium	Dysprosium-164	28.1	500	$^{164}Dy(n)^{165m}Dy$	1.25 min
			2,000	$^{164}Dy(n)^{165}Dy$	140 min
Gold	Gold-197	100	96	$^{197}Au(n)^{198}Au$	2.7 d

(a)The data for this table were obtained from references 9, 10, and 11.
(b)Metastable excited states are indicated by the m designation, as in reference 9.

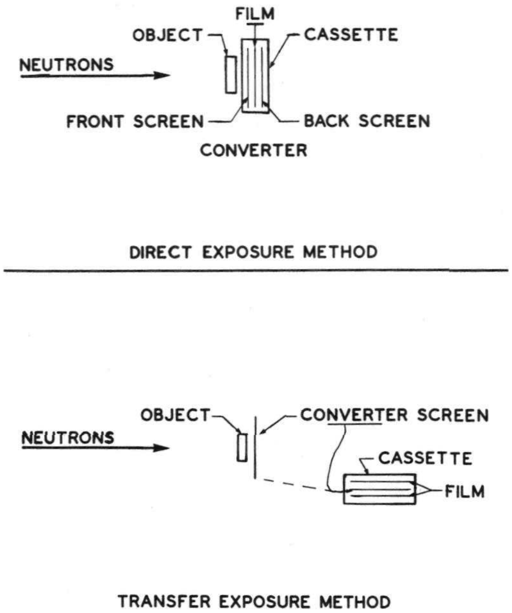

Figure 2

Arrangements Used for Direct Exposure and Transfer Neutron Radiographic Detection Are Illustrated

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For the most part these materials are best used in the form of thin metal screens. Exceptions to this rule occur in the case of the alpha emitters lithium and boron, which appear to yield much faster photographic neutron response when combined with a phosphor, so that light provides the principal photographic effect.[3] Preparation methods,[12-15] relative photographic speeds,[8,16] and radiographic applications[17] of such materials have been described.

The other detection technique, the transfer method, illustrated in Figure 2, does not employ photographic film in the actual neutron exposure. The neutron detector consists of a metal foil which becomes radioactive in proportion to the neutron intensity at each point in the image. This radioactive, image-carrying foil is then used in conventional autoradiographic methods to yield a photographic image of the neutron signal. This technique is usually not as fast as the direct exposure method, but it does have the advantage that the resultant radiograph is not influenced by interfering gamma radiation which may be present because of the neutron beam itself, prompt emission from objects in the beam path, or from a radioactive inspection object.

III. CHARACTERISTICS OF PHOTOGRAPHIC DETECTOR

Many of the converter materials mentioned in the previous section have been studied in order to determine the screen thicknesses that yield the best speed and resolution properties, and to determine something of the radiographic contrast obtainable with the various detection techniques. In the following sections most of the data are summarized.

A. Considerations about Photographic Speed

The first efforts to determine the relative speed with which the various converter materials could be used to detect thermal-neutron images were attempts to optimize the screen thickness and location of the converter material. These materials, at least the metal screens, were initially used in a double-screen configuration as indicated in Figure 2. Data such as those indicated in Figure 3 were used to determine what thickness should be used for screens made of each converter material studied. This plot for cadmium screens indicates that a front-screen thickness (toward the neutron source) of 250 μ and a back-screen thickness of 500 μ will yield greater film response than other cadmium screen combinations for identical neutron exposure.

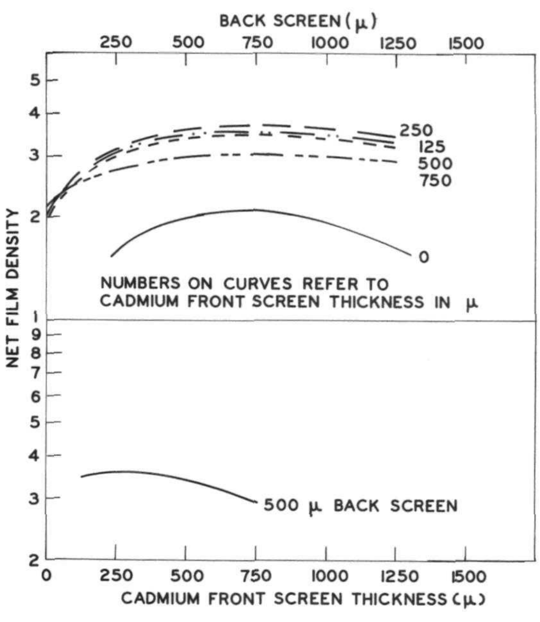

Figure 3

Film Densities Produced by Identical Neutron Exposures Using Different Thicknesses of Cadmium Converter Screens with Type KK X-ray Film

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A short-hand designation for this double cadmium screen arrangement is 250-500 Cd, where the numbers indicate the thicknesses of the front and back screens, respectively, in microns and the chemical symbol identifies the material. Similar data for double-screen use of other converter materials indicate that the screen combinations for best speed for each material are 250-250 Rh, 12-50 Gd, 500-750 In, 450-450 Ag, and

125-250 Dy. In each case the optimum speed screen thicknesses were taken at the points where screen thickness versus film-exposure plots tended to level off.

These data were obtained by using a monochromatic thermal-neutron beam having a wavelength of 1.05 A. A diagram of the beam arrangement is shown in Figure 4. This beam, providing a thermal-neutron intensity of 3×10^5 n/cm^2-sec over an area of about 7.5-cm diameter, has been very useful for the converter screen study because it was monochromatic, well collimated, and contained very little gamma radiation.(8,18) Further studies with a multi-energy neutron beam from Juggernaut reactor have tended to confirm these screen data.*

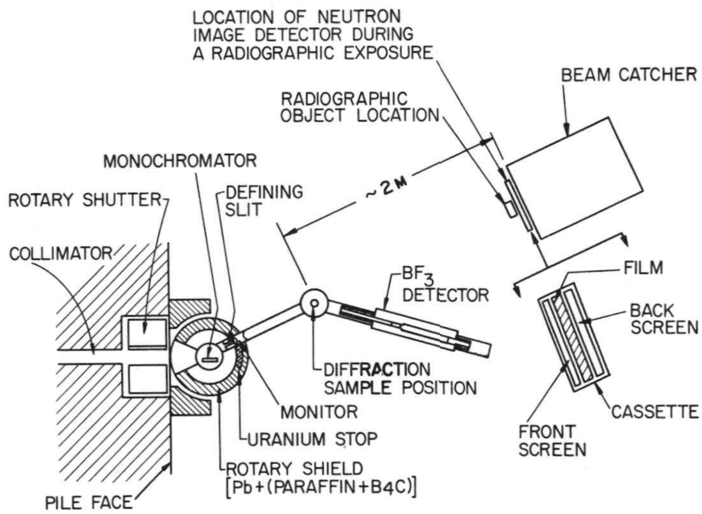

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Figure 4

Neutron-source Arrangement Used for Early Neutron-radiographic Studies

Once optimum double-screen data were available for a number of the converter screen materials, single, metal converter screens were used in further studies in an attempt to improve image quality. Although the emphasis here was on improved resolution, some studies were also made to determine the optimum single-screen technique from a speed point of view for each metal converter material. A typical plot for single rhodium converter screens is shown in Figure 5. The data indicate that best speed results with a single rhodium converter screen in a direct-exposure method can be obtained with a 250-μ-thick screen on the neutron-source side of the film. Best speed results with single metal screens were usually obtained with front screens, one notable exception being gadolinium, where the use of a back screen yielded the fastest result. The data for single gadolinium screens are shown in Figure 6. Data for other single screen converter materials have been given elsewhere.(19,20)

*This neutron facility is described in Sect. IV.

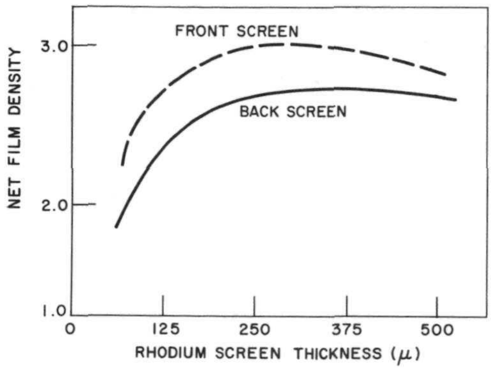

Figure 5. Determination of Single Rhodium Converter Screen Thickness and Location for Best Neutron Photographic Speed by Direct-exposure Method

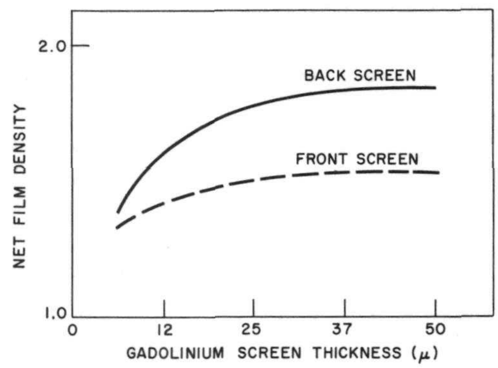

Figure 6. Determination of Single Gadolinium Metal Converter Screen Thickness and Location for Best Neutron Photographic Speed by the Direct-exposure Method

These single-screen speed data were obtained primarily to determine a useful compromise between speed and resolution characteristics for the exposure methods. A comparison of relative neutron photographic speed for many of the direct-exposure methods is given in Table II. The double metal screen thicknesses given in this tabulation were chosen because these gave the best speed results for a given converter material. The single metal screen thicknesses are compromises between best speed and best resolution properties. Scintillators, which yield the fastest response, were not varied in thickness.

The fast metal screen combination consisting of a rhodium front screen and a gadolinium back screen has the advantage that a front rhodium screen and a back gadolinium screen each yield fast results for a single metal screen direct-exposure method. When these two are combined in a double-screen technique, the result is a very fast metal screen method.(16)

By evaluation methods similar to those discussed above, the best screen thicknesses to use for transfer exposures have also been determined for several of the converter materials. Such data for indium and gold transfer methods have been reported(19) and indicate that the screen thicknesses for best speed should be about 500 and 125 μ for indium and gold, respectively. For the use of a dysprosium screen in a transfer technique, a screen thickness of about 250 μ has been reported to produce the best speed result.(20) In all these cases slightly faster results are obtained if the film is placed in contact with the neutron-source side of the transfer screen.

The data for transfer screens were obtained with the monochromatic neutron beam having an intensity of 3×10^5 n/cm^2-sec, an intensity that was insufficient to obtain such data for the materials of shorter half-life, rhodium and silver. With neutron exposure times and film transfer times in excess of three half-lives, so that the maximum possible film exposure was obtained, these screen materials yielded very light film exposures on fast X-ray films in this neutron intensity. Recent data with these materials in a higher neutron intensity beam at Juggernaut reactor* have indicated that best speed results are obtained with screen thicknesses of 250 μ for either rhodium or silver transfer screens.

Table II

RELATIVE PHOTOGRAPHIC SPEED FOR SEVERAL DIRECT-EXPOSURE NEUTRON IMAGE DETECTION METHODS

Converter Material and Screen Configuration[a]	Film Type	Relative Photographic Speed[b]
Li^6-enriched Scintillator as Back Screen[d]	F	50[c]
B^{10}-loaded Scintillator as Back Screen[e]	F	35[c]
Rhodium (250)-Gadolinium (50) Screens[f]	KK	1.6
Double Rhodium Screens (250-250)	KK	1.4
Double Gadolinium Screens (12-50)	KK	1.1
Double Indium Screens (500-750)	KK	1.1
Double Dysprosium Screens (75-250)	KK	1.1
Double Cadmium Screens (250-500)	KK	1.0
Double Silver Screens (450-450)	KK	0.8
Single Dysprosium as Back Screen (250)	KK	0.75
Single Gadolinium as Back Screen (25)	KK	0.71
Single Cadmium as Back Screen (250)	KK	0.67
Single Rhodium as Back Screen (250)	KK	0.62
Single Indium as Front Screen (500)	KK	0.5
Single Silver as Front Screen (375)	KK	0.35
Double Gold Screens (150-250)[g]	KK	0.3
Film Only - No Converter	KK	0.03

[a]Numbers in connection with metal screens refer to screen thicknesses for front screen and back screen, respectively, in microns.

[b]The relative photographic speed was obtained by comparing film densities for similar neutron exposures for each detector. The thermal-neutron intensity used was 3×10^5 n/cm^2-sec. All speed values have been compared with that of the double cadmium screen technique, which has arbitrarily been rated 1.0. Different exposure situations may change these figures somewhat because of different times required for the radioactive screen materials to reach saturation activities and because of reciprocity-law failures which may be encountered with the scintillators.

[c]The two speed numbers for the fast scintillator techniques are judged to be less accurate than the others because of the increased difficulty in controlling the very short exposures (1 to 3 sec) required.

[d]The lithium scintillator used was a 1:4 powder mixture of 96 per cent enriched Li^6F and ZnS(Ag). See references 15 and 16.

[e]The boron scintillator indicated here was the type described by Sun, reference 12.

[f] This combination of metal screens has yielded very fast results. See reference 16.

[g]The radioactive screen materials listed were all allowed a three half-life decay next to the film after the neutron exposure was completed. The gold screens were an exception to this rule in that only a one half-life decay period (2.7 days) was used. The speed number in this case would not have doubled with the use of the longer decay period because of the high contribution of prompt (n,γ) radiation during the actual neutron exposure. See reference 8.

*This beam facility is described later in Sect. IV.

B. Resolution Properties

Resolution studies on many of the photographic detection techniques have been made and reported.[21] In these studies use was made of a resolution test object consisting of a neutron-absorbing material through which a number of small holes were made, spaced apart a continuously decreasing distance. A neutron radiograph of a cadmium resolution test object is shown in Figure 7.

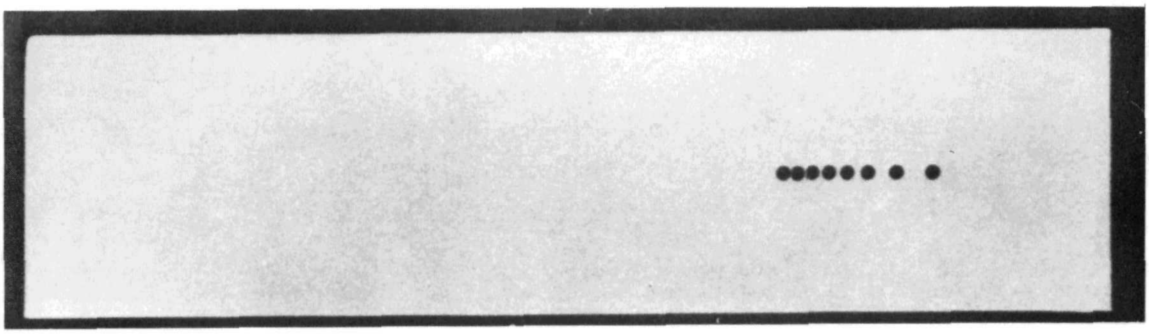

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Figure 7. A Neutron Radiograph of a Cadmium Resolution Test Object Is Shown. Hole diameters were 0.5 mm. Hole spacings varied from 30 to 750 μ.

Neutron radiographs of such test pieces, taken by many different photographic methods, were examined by a number of observers to determine the number of holes resolved on the radiograph. Admittedly, this method of determining resolution is subject to individual interpretation, and the results may not be capable of being expressed in terms of lines per millimeter resolution. A thinner test piece containing sets of slits would be preferable in this regard. Nevertheless, the much simpler test pieces used here did permit comparisons between different exposure methods and between different screen thicknesses for a given exposure method. These therefore did accomplish the purpose of the test, which was to determine screen thicknesses and methods for best resolution qualities of available neutron-radiographic imaging methods.

All neutron exposures were made with the test object directly on the outside surface of an aluminum-front, spring-loaded X-ray cassette. In order to be consistent throughout, the cassette was also used to position metal foils for transfer exposures. All films were processed and handled in a uniform manner in order to make the comparisons valid. Films were developed in Kodak liquid X-ray developer ($20 \pm \frac{1}{4}$°C) for 5 min without agitation.

Two resolution test pieces were used in these studies: a cadmium test piece, shown in Figure 7, and a thinner (50 μ as opposed to 500 μ for the cadmium test piece) gadolinium test object. The latter contained smaller-diameter holes (125-μ diameter for the gadolinium object, 500-μ diameter for the cadmium test piece) which were placed as close together as 10 μ between hole edges.

The best resolution converter material, gadolinium, produced neutron radiographs that were capable of resolving even this 10-μ spacing. Many of the detection methods were capable of resolutions in the order of 25 to 50 μ.

Some selected results of the resolution study are indicated in Table III.

Table III

RESOLUTION PROPERTIES FOR SELECTED CONVERTER MATERIAL DETECTION TECHNIQUES

Converter Material	Exposure Technique	Film Orientation[a] for Best Resolution	Screen Thickness[b] for Good Resolution (μ)	Resolution[c] Observed (μ)
Gadolinium	Direct	Front	12.5	10
Cadmium	Direct	Front	75	30
Rhodium	Direct	Front	75	50
Indium	Direct	Back[d]	125	50
Li^6 Scintillator[g]	Direct	(e)	(f)	50
B^{10} Scintillator[h]	Direct	(e)	(f)	50
Gold	Transfer	Front[i]	75	25
Indium	Transfer	Front[i]	50	50
Dysprosium	Transfer	Front[i]	250	50

[a] A front film indicates that film was used on the neutron-source side of the conversion screen, for both direct and transfer methods.

[b] The thicknesses indicated are for the fastest-response screens which yielded best resolution from among the particular screen thicknesses studied. In some cases, such as rhodium, the thinnest screen available yielded best resolution. A thinner screen, therefore, might yield an improved resolution result.

[c] Resolution indicated is the distance between holes in a neutron-absorbing test piece that could be just resolved on the resultant neutron radiograph by a majority of observers. The 10-μ spacing was the smallest available on the test objects.

[d] Indium screens appeared to yield better resolution when back films were used, as did silver screens. These were the exceptions to the metal screens studied in that the others all yielded better resolution with front films. See reference 21.

[e] Scintillators were used only with front films.

[f] Scintillators were not varied appreciably in thickness.

[g] A powder combination of 1 part (by weight) 96% enriched Li^6F and 4 parts ZnS(Ag). See references 15 and 16.

[h] A Sun-type scintillator, 92% enriched with B^{10}. See reference 12.

[i] With all transfer radiographs the use of front films is slightly preferable.

C. Radiographic Contrast

Although this phase of the neutron radiographic detector study has not been extensive, thickness variations in most metals of the order of

2 per cent of the base material thickness can be detected by neutron radiography. Comparing the detection methods for their contrast capabilities, one would conclude that transfer techniques generally yield better contrast than direct-exposure methods. This appears to be true because interfering gamma radiation, such as prompt (n,γ) radiation generated in the inspection sample itself, is not detected by transfer methods. This being the case, thickness variations in metals as low as 1 per cent have been detected by transfer methods.

Direct-exposure methods, on the other hand, do respond to prompt (n,γ) radiation. Therefore, some decrease in thickness sensitivity has been encountered in inspecting larger thicknesses of materials that have a greater tendency for prompt emission upon neutron bombardment. These aspects of the contrast problem will be discussed in more detail in a later section of this report.

As a general rule, the use of metal converter screens in direct-exposure methods does yield neutron radiographs on which 2 to 3 per cent variations in the inspection material thickness can be detected. Scintillator techniques were somewhat inferior in that they could detect thickness variations only in the range from 6 to 10 per cent. There appears to be no ready explanation for this poor contrast result obtained with scintillators.[22] Although recent work at this Laboratory indicates that a relatively large change in light output from the scintillator is obtained for a small change in neutron intensity (changed by varying reactor power level), the film results indicate that, with an inspection sample in place, only relatively large changes in sample thickness can be detected.

D. Relative Neutron-Gamma Response

A gamma-radiation image superimposed over a neutron image may completely obliterate the information desired from a neutron-radiographic inspection, since one of the primary advantages of this technique is that the relative absorption in materials for neutrons is quite different from that of gamma radiation. Therefore, the relative response of the detection methods to neutrons and gamma radiation is of some interest.

In one study[23] of this problem X-ray films used alone required an exposure of approximately 5×10^6 thermal neutrons/cm^2 to equal the response of one milliroentgen of cobalt-60 gamma radiation. Using metal converter screens, which improve the speed of thermal-neutron detection over that of film used alone by approximately 50 times, one would anticipate an improvement in this neutron to gamma response ratio by about that factor. Tests[6,20,24] do indicate that metal converter screens used in a direct-exposure method with X-ray film require an exposure of about 10^5 thermal neutrons/cm^2 to equal the film density produced by an exposure of one milliroentgen of cobalt-60 gamma radiation. For the faster neutron-detecting methods, such as the scintillator-film direct-exposure methods, this response ratio approaches 10^4 neutrons/cm^2/mR.

These response ratios can be of importance in a number of inspection situations, such as those which involve combinations of light and heavy materials. If one were inspecting boron-steel samples to determine the uniformity of the boron distribution, for example, the neutrons would yield a potentially high-contrast image because of the high neutron absorption of boron and the lower absorption in steel. However, if the neutron beam also contained a high gamma intensity, this contrast would be reduced if the detector also responded to the gamma radiation, because of the reversed absorption characteristics. In this case, therefore, a knowledge of the relative neutron to gamma response of the direct-exposure detection methods would be useful. The relative neutron to gamma intensities in the imaging beam might indicate that only a transfer detection method, which does not respond to the gamma radiation, would yield a useful inspection.

Fortunately, the transfer method is available for these inspection situations in which the anticipated neutron to gamma intensity ratio is so low that a large percentage of a direct-exposure detection would be yielded by the gamma radiation.

E. Recommended Detection Methods

Although some indication of recommended detection methods has been given previously,[7,18] it may be useful here to give the detection methods that have found the greatest use in the past year at this Laboratory. For direct exposure, the use of a single gadolinium metal screen and the use of a rhodium front screen with a gadolinium back screen have been employed to a great extent. The single gadolinium screen method has received extensive use because of the excellent resolution, which can be obtained with reasonable speed. The double-screen technique, yielding resolution results almost as good as with the single gadolinium screen technique, has been used when improved speed was required.

For transfer exposures, indium has been used extensively in in 250-μ thickness because it is readily available at reasonable cost. Admittedly indium is not as fast as dysprosium, nor does it yield quite as good resolution as gold. Nevertheless, indium does yield useful inspection results for the majority of applications.

IV. NEUTRON SOURCES

The neutron spectrometer source used in the early phase of this study, and shown in Figure 4, was useful for the investigation of various converter materials for detecting neutrons photographically because it was monochromatic, well collimated[20,21] and contained a very low intensity of gamma radiation.[18] When used practically for radiographic inspection, however, this source covered an area that was somewhat smaller than one would like. The most intense part of the beam covered roughly a 1- by 2-cm oval area; the beam spread to cover a total area approximately 7.5 cm in diameter. In addition, a neutron intensity somewhat greater than the value of 3×10^5 n/cm^2-sec available from the spectrometer source was desirable.

A second reactor source, in which the beam was used directly as it emerged from the reactor, was placed in operation at the Juggernaut reactor. The section view of the reactor shown in Figure 8 outlines the eight horizontal beam facilities available at this reactor for neutron experiments. In addition there are 14 vertical ports.

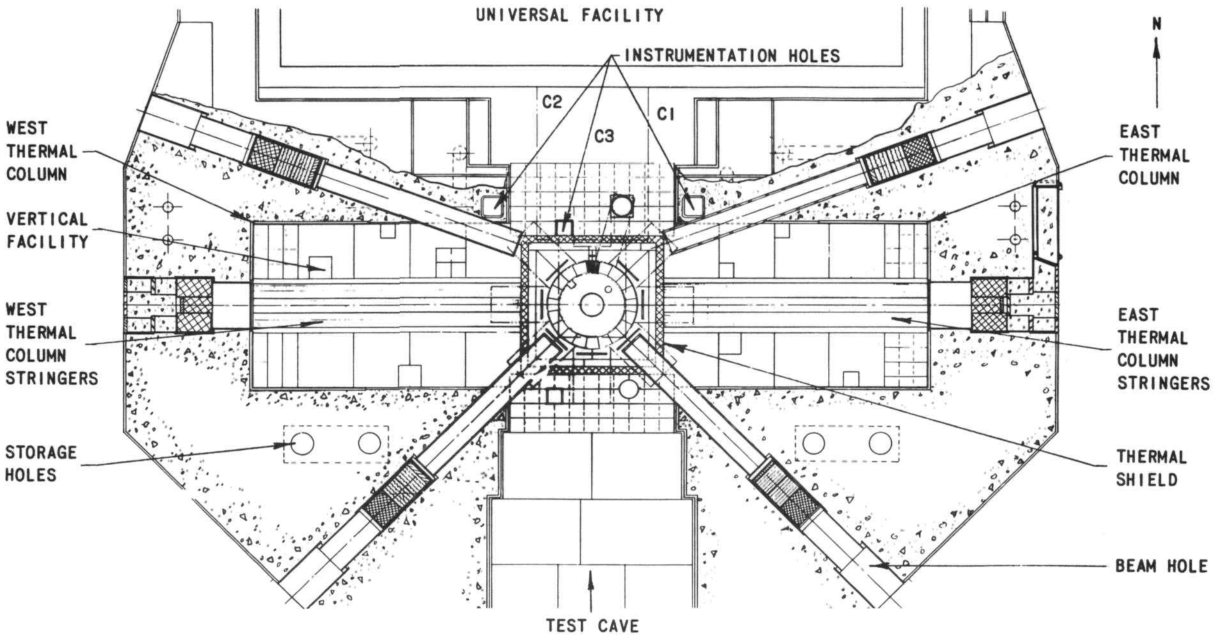

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Figure 8. A Section of the Juggernaut Reactor at 63.5-cm Elevation

For the neutron radiography study the choice of a beam facility was limited to the horizontal plane in order to simplify set-up problems, particularly those involving heavy inspection objects. Since it was further desired to obtain a well-collimated, external neutron beam, attention was centered on the four beam-hole facilities, these being of two different types. The beam holes on the southeast and southwest faces of the reactor extend through the lead thermal shield to within 7.5 cm of the face of the reactor vessel. The two beam holes on the northeast and northwest walls of the reactor extend in only to the thermal shield, and do not penetrate it.

The latter type was regarded as preferable since the thermal shield (lead, 5 cm thick) would be expected to reduce the gamma intensity in the beam and because the greater amount of moderating material in the neutron path (consisting primarily of the graphite reflector inside the thermal shield) would be expected to provide a more favorable thermal to fast neutron intensity ratio. The horizontal beam tube on the northeast face of the reactor was chosen and has been used for the neutron radiography study reported here.

The radiographic arrangement outside the reactor utilized a shielding wall to keep scattered radiation from entering an adjacent experimental area and a beam catcher, which contained the emergent beam and also provided a convenient location for radiographic detectors and objects. The exposures were remotely controlled by opening and closing the shutter inside the reactor wall. The experimental arrangement is shown in Figure 9.

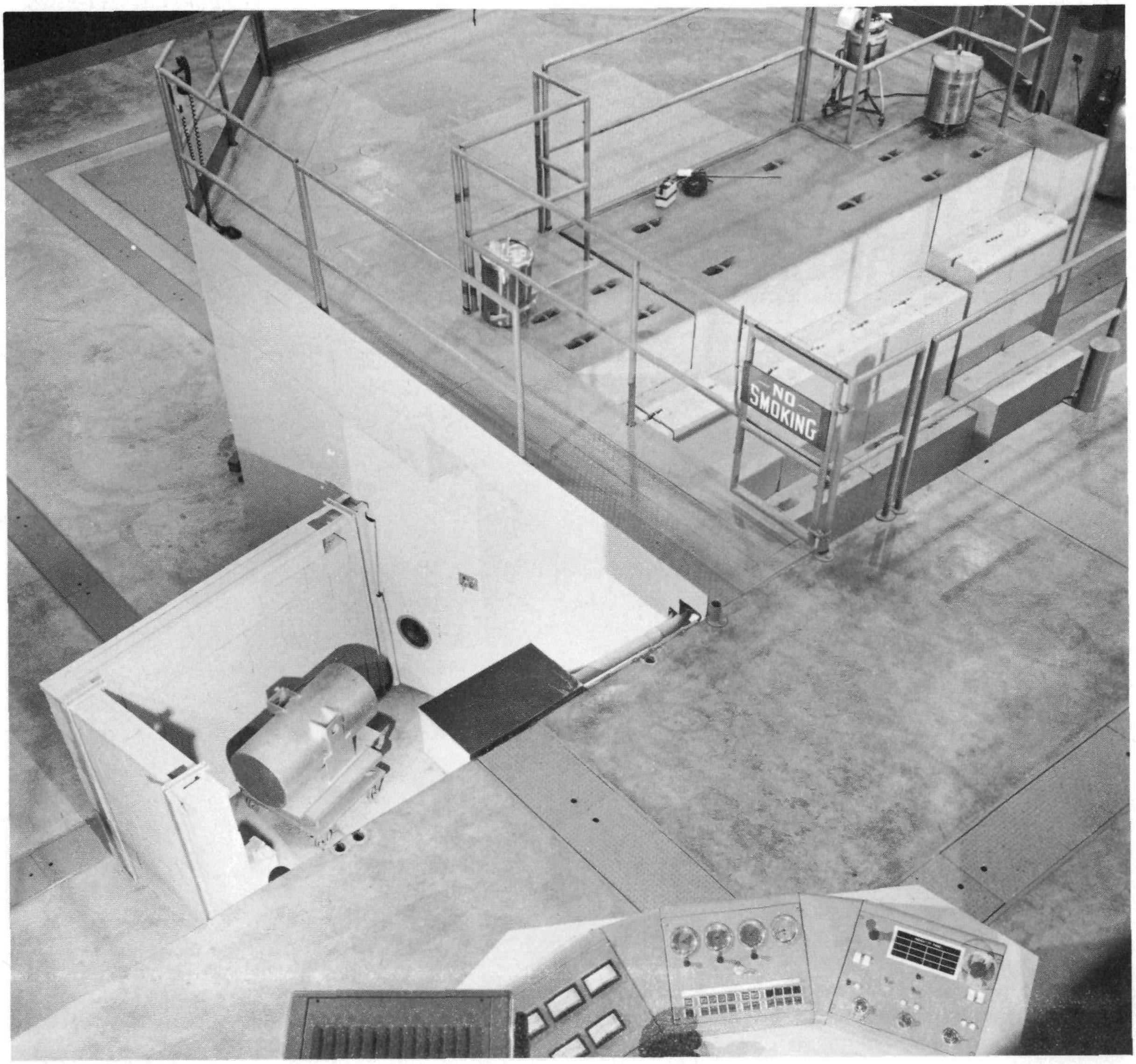

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Figure 9. A Photograph of the Neutron Radiographic Facility at Juggernaut Reactor

The beam arrangement normally employed for application studies utilized a stainless steel-lined, high-density-concrete beam collimator extending almost the entire length of the reactor beam tube, except for the shutter area. The collimator confined the emerging neutron beam to a rectangular area approximately 6.3 by 10 cm. Two different thicknesses of solid graphite were normally used at the reactor core end of the beam tube to improve the moderation of the emitted neutron beam.

With a graphite plug 12.5 cm long in the beam tube, the emergent beam had a total neutron intensity of 4.5×10^7 n/cm^2-sec, a cadmium ratio* of 2.4, and a gamma intensity of 110 R/hr. Another useful beam configuration involved a graphite plug 37.5 cm long and yielded a total neutron intensity of 1.5×10^7 n/cm^2-sec, a cadmium ratio* of 3.6, and a gamma intensity of 42 R/hr. All measurements were made at the reactor wall with the reactor operating at a power level of 200 kW. These two beam configurations at the Juggernaut facility have been used for a wide variety of application studies. This will be discussed below. A more detailed report describing this reactor beam facility has been given elsewhere.[25]

Although this study has been concerned almost entirely with these reactor neutron sources, some indication of other possible neutron sources should be made. Accelerator and radioactive neutron sources for this application are feasible, although the situation is complicated by the fact that most sources of this nature yield higher-energy neutrons, which should be moderated before being applied for general radiographic use. Some techniques for accomplishing this moderation and then bringing a useful thermal neutron beam out of the moderator have been described.[2-5] Because of the large loss in neutron intensity one encounters in going from a fast-neutron yield to a collimated thermal-neutron beam from a moderator, relatively high-intensity fast-neutron sources are required in order to obtain a reasonable neutron intensity for radiography. Indications are that, in going from neutrons having energies in the MeV range to a collimated thermal-neutron beam, the loss in intensity will be of the order of 10^6 times.[6,19] A fast-neutron yield of 10^{10} neutrons/sec would therefore produce a collimated thermal neutron beam intensity of about 10^4 n/cm^2-sec, which is about the minimum intensity one would regard as practical for general neutron radiography. A number of neutron sources having total yields in the order of 10^{10} neutrons/sec and higher are available.[26,27]

If, on the other hand, one can start with neutrons of lower energy, such as the 25-keV neutrons from a radioactive Sb-Be source, the loss in intensity might not be as great. Warman[28] has indicated that it was possible to obtain a collimated thermal-neutron beam intensity of about 10^6 n/cm^2-sec from a 10^{10}-n/sec yield Sb-Be source.[29]

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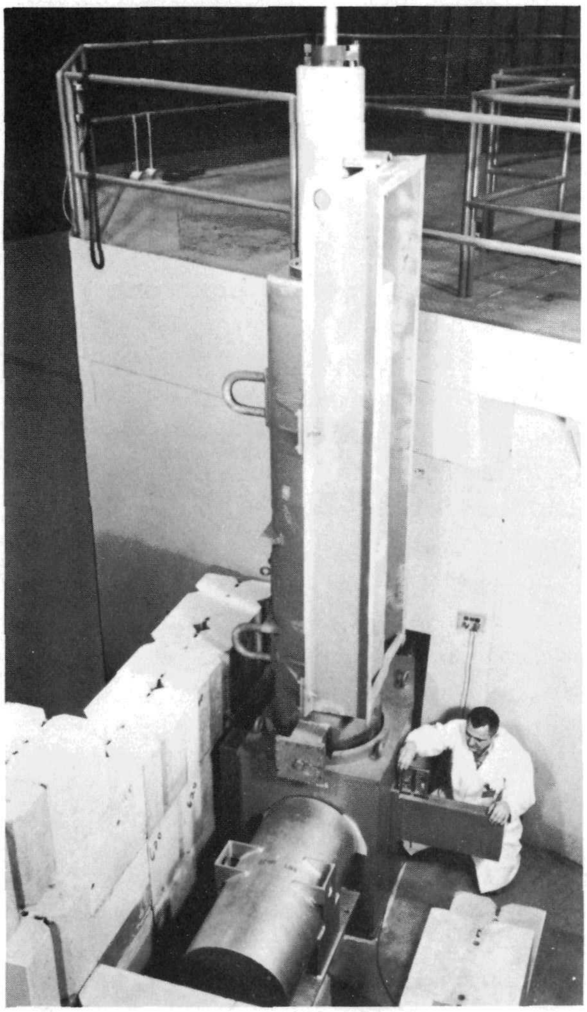
*Cadmium ratios were determined with bare and 0.5-mm-thick cadmium-covered gold foils.

This problem of obtaining useful radiographic neutron beams from neutron sources other than nuclear reactors is the key to broadening the usefulness of neutron radiography as an inspection technique. At this writing, additional effort in this area does seem necessary.

V. APPLICATIONS

The applications of neutron radiography have been concentrated primarily in three general areas of appreciable interest in the nuclear field, involving the neutron inspection of radioactive materials, reactor control materials, and heavy metals. In addition, there have been a few application efforts that can be grouped into a fourth, miscellaneous category.



106-7338

Figure 10. The Photograph Shows the Facility for the Inspection of Radioactive Fuel Capsules Adjacent to the Juggernaut Reactor

To date, at this Laboratory, the inspection of radioactive material has been the principal application of neutron radiography. Neutron radiography is very useful in such inspections because when the transfer exposure method is used, the detector does not respond to the gamma radiation from the inspection object. Therefore, as long as adequate personnel shielding can be accomplished, the activity level of the inspection object presents no problem.

The neutron technique has been used to inspect a large number of irradiated reactor fuel specimens[30,31] whose activity levels have ranged up to 500 R/hr at one meter. These inspections are now handled on a routine basis with an arrangement pictured in Figure 10. A diagram of the apparatus[32] is shown in Figure 11. A comparison of the neutron inspection results, the inspection result obtained from a pin-hole camera[33] and a photograph of the sample in the cave facility after disassembly is given in Figure 12.

In addition to the obvious improvement in the quality of the inspection result obtained with neutron radiography in contrast with pinhole

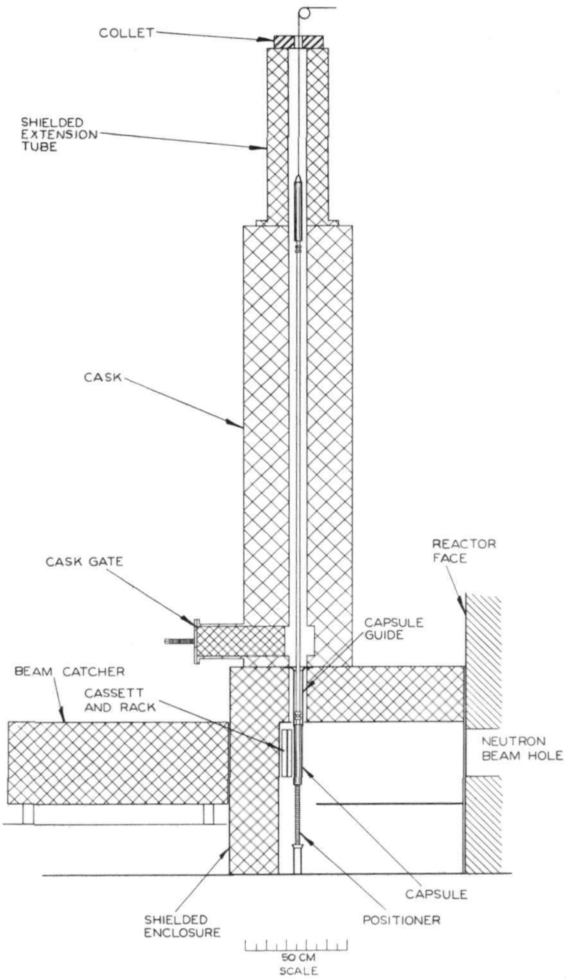


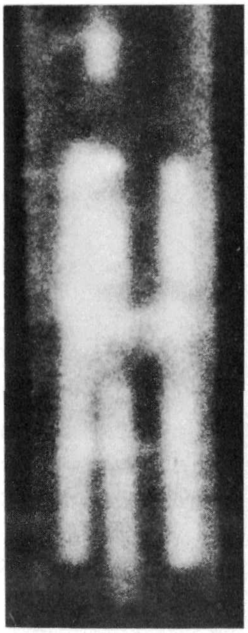
Figure 11

A Diagram Showing the Essential Features of the Equipment Pictured in Figure 10

106-7502

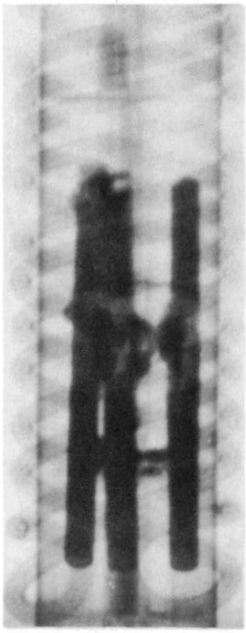
Figure 12

A Pinhole Autoradiograph and a Neutron Radiograph (Both Positive Prints) of a Radioactive, Unopened Fuel Capsule Are Compared with a Photograph of the Opened Capsule

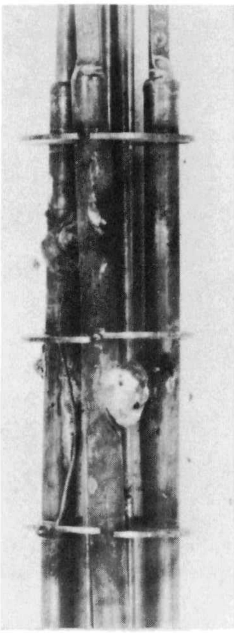


106-7003

Gamma Autoradiograph of Unopened Capsule



Neutron Radiograph of Unopened Capsule



Optical Photograph of Clad Fuel Specimens after Capsule Was Opened autoradiography, the neutron technique also has the advantage that other objects within the inspection capsule, such as thermocouples and spacers, show up on the radiograph. The pinhole method, on the other hand, usually yields information only about the fuel itself. In addition, the neutron technique has an advantage over X-ray techniques[34,35] in that the latter have some upper limit of sample radioactivity beyond which film fogging becomes so excessive that the inspection cannot yield useful results.

Neutron radiography also offers some unique advantages in the inspection of reactor control materials, both in regard to uniformity[18] and to the determination of burnup.[36] Since such materials are originally chosen because of their high neutron-absorbing properties, the use of neutrons to inspect them does seem logical.

An example of the use of neutron radiography to determine the uniformity of the distribution of a neutron-absorbing material within another material is shown in Figure 13. The inspection objects were experimental samples of B_4C and glass powder mixtures in stainless steel tubes. The neutron radiographs easily show variations in the uniformity of the distribution of the boron within the samples.

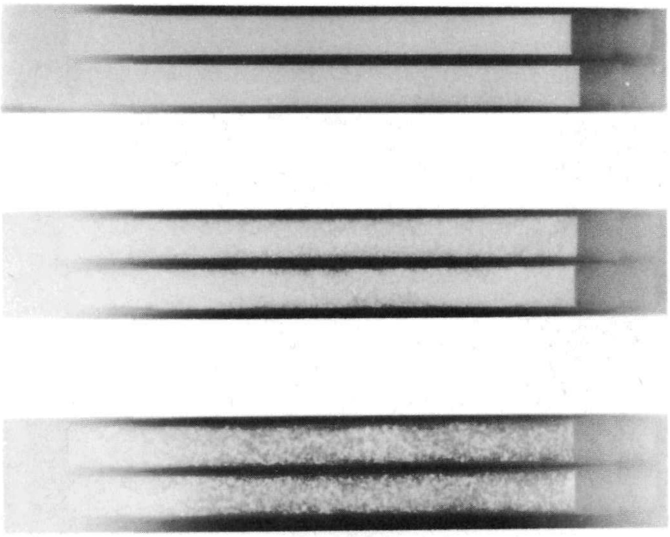
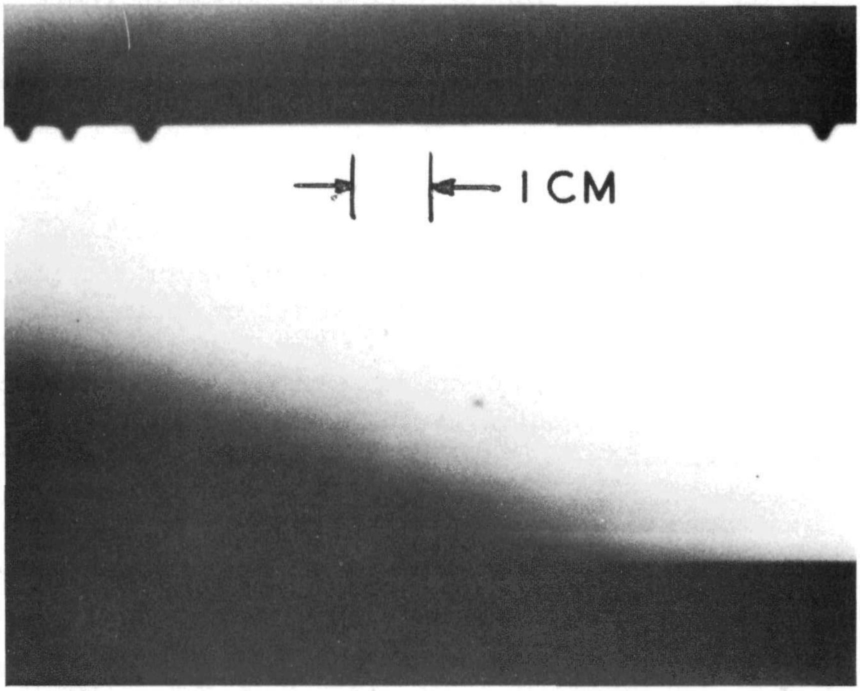


Figure 13

These Neutron Radiographs of B_4C and Glass Powder Mixtures Sintered in Stainless Steel Tubes Show the Varying Degree of Uniformity of Mixing Obtained and Indicate the Sensitivity of the Neutron Technique for Making Such Inspections

38340

The neutron technique is particularly well suited to the determination of high burnup in reactor-control materials since the relative neutron absorption in each area of the control material can easily be shown by neutron radiography. Such a study was recently made of a cadmium shim-safety rod removed from CP-5 reactor after a long period of use.[36] Neutron radiographs of this material, having a nominal thickness of 0.625 mm, were compared with normal, unirradiated cadmium. The inspection indicated that the irradiated cadmium had an equivalent normal cadmium thickness of less than 0.025 mm in the highly irradiated areas and that the transition between this area and the essentially normal cadmium area was surprisingly abrupt (see Figure 14). The advantage of using neutron radiography for this type of inspection is that a complete picture of the burnup pattern can be obtained very rapidly. If more accurate determinations of burnup are required, the neutron radiographs obtained can be used to advantage in locating specific areas of interest for further study by chemical, mass spectrometric, or other methods.



37911

Figure 14. This Neutron Radiograph of One Portion of a Used Cadmium Shim-safety Rod Indicates the Depletion of Cd^{113} in the Area on the Left by the Much Higher Neutron Transmission through This Area

The third major area of application for neutron radiography at this Laboratory has been the inspection of heavy metals, primarily uranium and plutonium (see Figure 15). The advantage of using neutrons for such inspections lies in the fact that the absorption of neutrons is appreciably less than is the case with most X radiations. Further, heavy sections can be easily inspected. A comparison of exposure times for several X-radiographic and neutron-radiographic methods for natural uranium(37) indicates that thermal-neutron sources of reasonable intensity (10^6 n/cm^2-sec or more) can provide good-quality inspections of a few centimeters or more of heavy material with exposure times comparable with those required when a Betatron X-ray source is used. Contrast sensitivities of the order of 1 to 3 per cent can be obtained by neutron radiography.

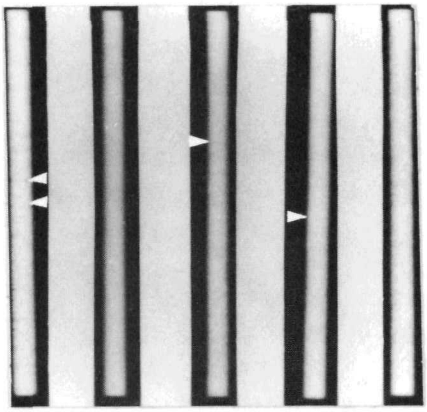


Figure 15

A Neutron Radiograph of Several Plutonium Pins (Separated by Strips of Cadmium) Shows Evidence of Cracks (White Arrowheads Indicate Several Cracks) in Many of the Pins. The length of each pin was about 5 cm.

39090

Reported neutron radiographic studies[17,37-39] of heavy metals indicate that neutron radiography is particularly useful for the inspection of natural uranium, lead, and bismuth. The use of neutrons to inspect steel, however, presents fewer advantages because the attenuation differences are less favorable and because steel does emit appreciable prompt (n,γ) radiation upon neutron bombardment. As pointed out previously, this prompt radiation tends to decrease the contrast obtained with direct-exposure neutron techniques, particularly in the inspection of larger thicknesses. The effect can be eliminated by using transfer detection methods, although in this case, too, a limiting inspection thickness is encountered because of saturation effects for the transfer materials.[39]

Neutron radiographic methods have been used to study crystal orientation in thin metal samples,[40] biological samples,[41-43] and hydrogenous materials.[39] Although neutron radiography does not appear to be a good tool for inspecting relatively large thicknesses (several centimeters or more) of hydrogenous material, because excessive scatter greatly reduces the variation in thickness which can be detected, the neutron technique may be of value in inspecting thinner hydrogenous samples or hydrogenous materials combined with heavier materials. In the latter case, neutron radiography may provide the only means of radiographic inspection.

In such cases, the hydrogen content may have to be fairly large in order to detect significant differences. For example, a neutron radiographic study[44] of several small (1 x 4 x 0.01-cm) Zircaloy-2 coupons containing various amounts of hydrogen indicated that the hydrogen content would have to be at least 5000 ppm before meaningful variations in hydrogen content could be detected by neutron radiography. Nevertheless, useful neutron inspections of hydrogenous and heavy material combinations have been reported.[27]

The biological applications of neutron radiography have not been investigated extensively as of this time. However, a study now in progress[42] to determine the usefulness of various neutron contrast agents in biological systems may indicate the direction of further efforts in this area. Special biological applications have also been suggested by Barton.[43] From an industrial radiographic point of view, the use of neutron contrast agents to improve radiographic contrast has already been demonstrated.[6]

VI. CONCLUSIONS

Methods for inspecting by neutron radiography have been demonstrated and are being applied to a wide variety of inspection problems. It seems reasonable to anticipate that the future availability of neutron sources other than nuclear reactors will contribute to much wider application of this technique in industry.

VII. ACKNOWLEDGMENTS

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